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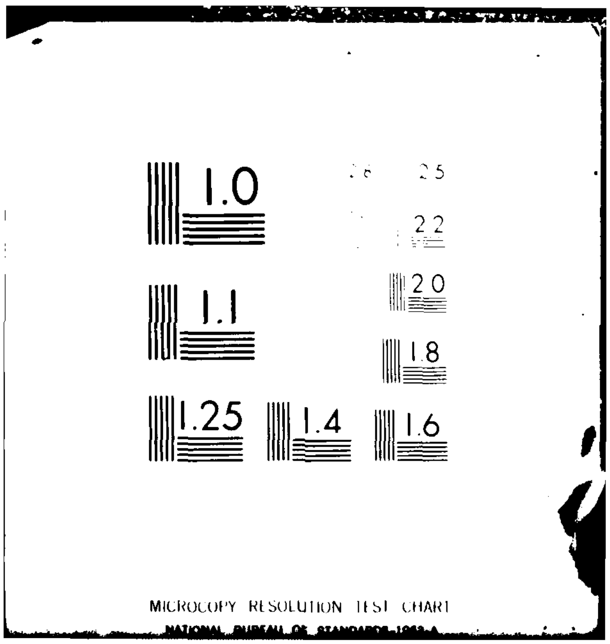
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AUTOMOTIVE COLD-START CARBON MONOXIDE EMISSIONS AND PREHEATER EVALUATION

Harold J. Coutts

Prepared for
U.S. ENVIRONMENTAL PROTECTION AGENCY
CORVALLIS, OREGON
By

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Fairbanks and Anchorage, Alaska, experience high wintertime ambient levels of carbon monoxide (CO). Emissions from starting automobile engines in cold weather are thought to be a major source of CO. A quantitative procedure for determining startup CO emissions was developed. The startup emissions were measured as a function of soak time at several low ambient temperatures. The performance of engine preheaters in reducing the startup CO at the various soak times and temperatures was estimated. The data scatter was too great to draw any firm conclusions; however, the length of cold-soak time appeared to

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have a stronger effect on cold-start CO emissions than did soak temperatures (0 to -30°C). Compared to no preheat, continuous preheat during an overnight cold soak can reduce the cold-start CO emissions by 20 to 90%.

PREFACE

This report was prepared by Harold J. Coutts, Research Civil Engineer, Alaska Projects Office, U.S. Army Cold Regions Research and Engineering Laboratory. Funding was provided by the U.S. Environmental Protection Agency, Corvallis Environmental Research Laboratory, through Interagency Agreement EPA-79-D-F0847.

The author thanks the following individuals and organizations for their valuable assistance in this project. The testing program could not have been as successfully completed without the help of T. Moyer, M. Hoyles, and A. Frizzera of the Alaska Department of Environmental Conservation who supplied equipment and test instrumentation, and actively participated in the setup and running of the cold-start tests; D. Moore of the Environmental Services Department of the Fairbanks North Star Borough who supplied two exhaust gas analyzers and other instrumentation; T. Scarborough of Scarborough and Associates who supplied the fuel scales and small tanks; S. Brown of the University of Alaska physical plant who supplied the kWhr meters; the Fort Wainwright facility engineers who installed lighting and repaired the furnace in the test building; and Fairbanks Datsun and CRREL's motor pool who supplied the test vehicles.

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by

Harold J. Coutts

INTRODUCTION

BACKGROUND

Fairbanks, Alaska suffers from air pollution even though it is located in a relatively underpopulated state. The Fairbanks air pollution problem has three major components: carbon monoxide (CO), ice fog and particulate matter.

Mobile sources (cars and trucks) are major contributors of these and other pollutants, including nitrogen oxides and hydrocarbons (HC). Lead is the major particulate emitted from vehicles using leaded gasoline. In Fairbanks, gross particulates, CO, and lead particulates are the only pollutants exceeding the national ambient air quality standards. Time will take care of the lead problem as leaded gasoline is slowly phased out, but other particulates will continue to be a problem.

Cars and trucks are the major source of CO, but not all particulates. Besides Fairbanks, Anchorage also experiences high ambient levels of CO during the winter. For many years it has been known that those levels are attributable to mobile sources (Holty 1973). Startup of cold automobile engines is now suspected to be a major contributor to the high CO levels. Cold-start automotive emissions are those high concentrations of CO and HC emitted during the first few minutes after startup of a cold gasoline-fueled engine.

In 1973 it was speculated that cold-start emissions could be the worst contributor to air pollution from automobiles used in cold regions (Coutts et al. 1973). Further research in 1974 and 1975 indicated that cold-start emissions were clearly responsible for approximately 66% of the ambient CO in the Fairbanks central business district (Fairbanks North Star Borough 1977).

Something must be done to alleviate the high cold-start emissions if Fairbanks and Anchorage are to have cleaner air. This study will evaluate one method for limiting high cold start emissions: engine preheaters.

Preheater devices warm an engine so that it acts as if it is in a warmer climate and emits less CO during cold start. In an attempt to determine the efficiency of preheater devices, the Fairbanks North Star Borough supported a small research contract to conduct cold-start tests with and without engine preheaters. That study resulted in a report entitled Evaluation of automotive engine preheaters as a technique to control cold start carbon monoxide emissions (Leonard et al. 1978). In the introduction (p. 4) the authors state: "As with previous vehicle emissions research in Fairbanks, a lack of quality test facilities such as environmentally controlled test chambers and sophisticated instrumentation has greatly limited the precision of the test procedure which, in turn, reduces our confidence level in the resulting data." The funding level for that study was not sufficient to purchase the Constant Volume Sampler (CVS) system used in the Environmental Protection Agency's (EPA) federal test procedure; so exhaust emissions were estimated using exhaust gas analyzers.

Late in 1979, the EPA negotiated an interagency agreement with CRREL's Alaskan Projects Office to further investigate the character of cold-start emissions and the performance of preheaters in reducing these emissions. The initial funding level for this study was also not sufficient to allow utilization of the EPA's Federal Test Procedure using a Constant Volume Sampler (FTP-CVS).

SCOPE

The interagency agreement between CRREL and the EPA stated that initial studies will include the following:

1. Characterization of emissions from specific automobiles as a function of cold-soak and preheat time, and temperature during cold-starting conditions.

2. Determination of the relationship between emissions, time of engine cool-down, amount of engine preheating, and energy consumption for specific vehicles.

The interagency agreement also stated that "CRREL plans to cooperate with the Alaska Department of Environmental Conservation in accomplishing the objectives of this agreement." In addition to preheater evaluation,

the Alaska Department of Environmental Conservation requested that CRREL develop a quantitative procedure for measuring exhaust emissions and then compare it with an earlier procedure developed in 1973 (Coutts et al. 1973).

Development of the quantitative procedure was the first major objective of this study. The procedure developed in 1973 assumed that the engine was a positive displacement pump (engine displacement) and calculated volumetric emissions on that basis. The engine displacement procedure has been used for over 600 tests. If those results could be correlated with a more quantitative procedure, they would be accepted by agencies responsible for developing plans to reduce air pollution. The more quantitative procedure involved bagging the total exhaust volume.

The intent of this project was to quantify cold-start CO emissions from 100 total tests using three different vehicles and to determine the effectiveness of preheat in reducing those emissions. The tests were conducted in Fairbanks from December 1979 through February 1980. They involved various cold-soak times at several temperatures with and without preheat. The preheat devices tested were those in most common use today.

The EPA-approved federal test procedures (FTP-CVS) were not used because cars would stall due to insufficient warmup at -18°C. The EPA driving schedule cycle used in the FTP-CVS includes only a 20-second warmup time. The cold-start tests in this program did not involve any loaded engine (moving vehicle) operation, so the results will never be directly comparable to the FTP-CVS. However, it is felt that the total exhaust capture (bag) method used in this study provides accuracy comparable to the FTP-CVS. The study was limited to cold-start tests on gasoline-fueled, spark ignition engines. CO was the only cold-start pollutant measured.

TESTING MATERIALS AND METHODS

COLD START

There may be many definitions of cold start, but it generally means the period immediately after startup of an engine that has not recently been running. After startup, the engine is allowed to idle until it is warm enough for driver comfort and to avoid stalling. Leonard defined the cold-start mode "... as the period of vehicle operation beginning with

initial start-up and continuing until normal operating temperature (60 to 95°C) is reached" (Leonard 1978, p. 7).

Cold start yields higher concentrations of CO and HC than any other vehicular operating mode. The cold-start effect is basically the result of choking which causes more fuel (HC) to enter the engine than it can effectively burn. Emissions of CO and HC are a major result of this incomplete combustion. The effect of air-to-fuel ratio upon CO emissions is discussed in Appendix A. Without choking, a cold gasoline engine would usually stall under the cyclic loading encountered during routine driving in populated areas.

During cold start, the exhaust CO concentration drops as the choke slowly opens. After the choke is open, the CO concentration remains relatively constant. Therefore, the cold-start tests were terminated when the exhaust CO concentration remained at a low, constant level for 1 min. This occurred consistently before 6 min with the two small test engines. Because the choke remained closed longer on the large engine, cold start was arbitrarily limited to about 6 to 8 min by the capacity of the sampling equipment.

Pollution control devices such as catalytic converters and air pumps are only effective in reducing warm engine CO and HC emissions (Leonard 1975). Therefore, even in warmer climates cold-start emissions are now producing a significant portion of total driving emissions. In recognition of this, the EPA drafted an advisory circular limiting the increase in emissions as temperature decreases (EPA 1978). However, because of industry protests that circular has been withdrawn.

The period of engine cool-down will be known from here on as the cold-soak time. Engine preheating was accomplished by electric resistance heaters. The amount of preheat was the length of time the heaters were plugged in; their energy consumption was measured in kWhr. Electric timers controlled the amount of preheat.

VEHICLES

Three vehicles, one with a large engine and two with small engines, were used in this study. The vehicle characteristics are listed in Table 1. Smaller engines were selected because large V8 engines appear to be losing their popularity and a large engine would require a much larger sampling bag. The engines tested were the I-block type, with in-line

Table 1. Vehicles used in cold-start tests.

	Datsun 210	Datsun 310	Dodge truck (1/2 ton)
Year	1976	1979	1979
Mileage	42840	1650	1026
Engine displacement (L)	1.40	1.40	3.69 (225 in.^{3})
Number of cylinders	4	4	6
Valve overlap	34°	34°	26°
CO emission control devices	Air pump	Air pump	Air pump & catalytic converter
Automatic choke control	Electrically heated housing which contains heat sensitive choke release coil.		Heat sensitive choke release coil mounted directly on exhaust manifold.
Preheaters	750-W tank type	750-W tank type	500-W tank type plus others

cylinders. The fact that the 1979 models had low mileage and were unconditioned vehicles was recognized and accepted. The EPA, however, routinely preconditions vehicles by driving them at least 6400 km (4000 miles) before testing emissions.

PREHEATERS

Engine preheaters have been in routine use in Alaska for many years. Many people have found that as the temperature drops below -18°C (0°F) their vehicles will not start after remaining outside overnight without some form of engine preheat. Preheating has two effects, it warms the lubricant at bearing surfaces to reduce the starting power requirement due to thick oils and it warms the engine head and part of the intake manifold causing more fuel vaporization for better ignition. The majority of the preheaters use electrical heating elements immersed in the vehicle's antifreeze solution. The heating element can be placed in the engine block (frost plug and head bolt preheaters) or outside the block (radiator hose and tank type preheaters).

The most common preheater is the tank type which acts as a thermosiphon reboiler. This preheater utilizes an antifreeze suction hose attached to the engine block, usually by replacing the coolant drain plug

with a hose connection. The heated coolant is returned to the block via a pipe wye tapped into the heater hose. Circulation is caused by the low density steam/antifreeze mixture exiting the tank via its upper hose. The circulation effect is exactly the same as that in a coffee percolator. Electricity is supplied to the preheaters by connecting extension cords to standard 120-V outlets. The tank type preheaters have built-in thermostats to prevent the heating element from melting if coolant is lost.

The three test vehicles were all equipped with tank type heaters. The Dodge truck also had an antifreeze circulation pump connected to the preheater and electric heating elements in the engine and transmission oil pans. Total power consumption of the truck's preheat system was 1.5 kW. The power consumption figures for the 210 and the truck were calculated from long term use of kWhr meters. The 310's preheater power consumption was calculated by measuring its short term current (amps) draw. Other types of engine heaters were not evaluated in this study.

TEST PROCEDURE

As stated earlier, the objectives of this study were to:

1. Develop a quantitative (bag) procedure for measuring cold-start emissions, and compare test results with those from the positive displacement engine procedure used in earlier studies.

2. Quantify cold-start emissions as a function of cold-soak time and temperature.

3. Measure the effectiveness of engine preheaters for reducing cold-start emissions and quantify preheater power consumption.

Due to funding limitations, only the vehicles listed in Table 1 were tested.

Test conditions

In the original plan of this study, tests were to be conducted at -6.7°, -18° and -29°C. Tests for each vehicle were to be conducted without preheat at -6.7° and -18°C with cold-soak times of overnight (14 hr or longer), 9, 4 and 2 hr. Duplicate tests were to be run using preheat. With-preheat tests at -29°C were to be conducted with overnight, 9-hr and 4-hr cold-soak times. At all temperatures, with an overnight cold soak, the preheat times tested were to be overnight (continuous), 4 and 2 hr. With a 9-hr cold soak, the preheat times were to be 9 (continuous) and 2

hr. [illegible] the 4-hr cold-soak time the preheat was to be continuous (4 hr). The engines with preheat were not to be allowed to cool before startup. Cold soaks of 14 hr or longer were to be labeled as overnight and not further differentiated because by that time the engine temperature with or without preheaters would no longer continue to decrease.

Test equipment

CO/HC analyzer. The exhaust gas analyzers used were Horiba Mexa 300s which used the nondispersive infrared absorption principle for measuring the concentration of CO and HC (hereafter called the CO/HC analyzer). Gasoline is a mixture of HCs from butane to nonane. Hexane, a most prominent component of gasoline, was chosen as the reference HC for calibration and readout.

The analyzer was calibrated with two span gases containing 1.5 and 10% CO. Normally the analyzer is equipped to read CO concentrations up to 10%, but it was modified to read up to 20% because at times the exhaust CO concentration exceeded 10%. The analyzers were equipped with sample pumps, a condensate trap and a particulate filter. There was so much exhaust soot and condensate (H_2O) that a larger external trap and filter assembly were attached to the inlet fitting. A 6-mm (1/4-in.) i.d. rubber hose was used as a sampling line. To prevent freezing, the sample line was traced with a heat tape and insulated with foam rubber.

Temperatures. Air and coolant temperatures were measured with type T thermocouples and a Fluke model 2100A digital thermometer.

Oxygen (O_2). A Teledyne model 320P oxygen meter was used to check the oxygen content of the exhaust gas. The dry gas exhaust line from the CO/HC analyzer was used to pipe the sample into the O_2 meter.

Engine speed. Engine rpm was measured with three electronic induction pickup tachometers. The probe (pickup) was clipped on one of the spark plug wires.

Induction and exhaust system pressures. Intake manifold vacuum was measured with a standard, portable manifold vacuum gage. Exhaust system pressures were measured with a diaphragm gage calibrated in inches of water.

Exhaust collection and measurement. The total exhaust volume from each cold start was collected in a large 3 x 3-m (10 x 10-ft) or 3 x 5-m

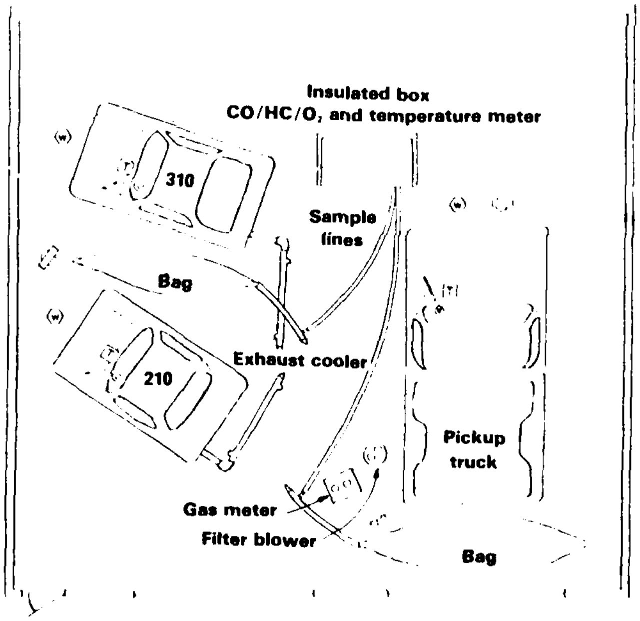
(10 x 15-ft), 0.15-mm (6-mil.) thick black polyethylene bag, then measured with a Sprague model 675 temperature-compensated gas meter.

Fuel type and consumption. A locally purchased winter grade of lead-free gasoline was used. The mass of gasoline used during each cold start was measured by weighing the fuel consumed from small fuel tanks hanging from spring scales.

Power consumption and timers. The electric power consumed by a preheater was measured by wiring General Electric kWhr meters into each power cord. Intermatic 24-hr electrical time switches were used to turn the preheaters on during some of the cold-soak periods.

Test building

A heatable, large, two-bay garage at CRREL's Fairbanks Farmers Loop site was used as the coldroom. The gas measuring instruments were placed in heated wood boxes and the large gas collection bags were hung from the upper garage door support rails. Figure 1 is a diagram of the garage layout.



Vacuum gage
Tachometer
Gasoline weigh tank
Timer and Whr meter

Figure 1. Layout of test building.

EXHAUST MEASUREMENT

The amount of exhaust CO was measured and calculated by two independent methods. One method is based upon engine displacement and the other on the collection of the total exhaust in bags.

Displacement method

The engine displacement method is an approximation method wherein the engine is assumed to be a positive displacement gas pump and the exhaust volume is assumed to be the same as the inlet air volume. This method was originally developed in 1973 (Coutts et al. 1973).

The exhaust CO volume in liters V at intake manifold temperature can be estimated from the following equation:

$$V = \left(\frac{29-\text{vac}}{29}\right) \text{RPM} \left(\frac{\text{E.D.}}{2}\right) \left(\frac{\%\text{CO}}{100}\right) T.$$

Where

29 = test site atmosphere pressure (in. of mercury assumed constant)

vac = manifold vacuum (in. of mercury)

$\frac{29-\text{vac}}{29}$ = manifold pressure (atm)

RPM = engine speed (rpm)

$\frac{\text{E.D.}}{2}$ = engine displacement per revolution; if present, air pump displacement must be included

$\frac{\%\text{CO}}{100}$ = fraction of exhaust that is CO

T = measuring time (min)

The assumptions made in developing the equation are:

1. Moles of exhaust gases are the same as moles of intake air.
2. Intake gas temperature is constant at 15°C (60°F).
3. There is no valve overlap, i.e., no direct open connection

between intake and exhaust manifolds. The manifold pressure term incorporates to some extent the volumetric efficiency. Since this method gives only a crude approximation, it was felt that corrections for temperature and the use of daily atmospheric pressure readings would falsely increase the reader's confidence in the results.

A discussion of the computations for this displacement method is in Appendix B. In using this method, the manifold vacuum, rpm, and % CO were recorded every 15 seconds after starting. When the exhaust CO concentration

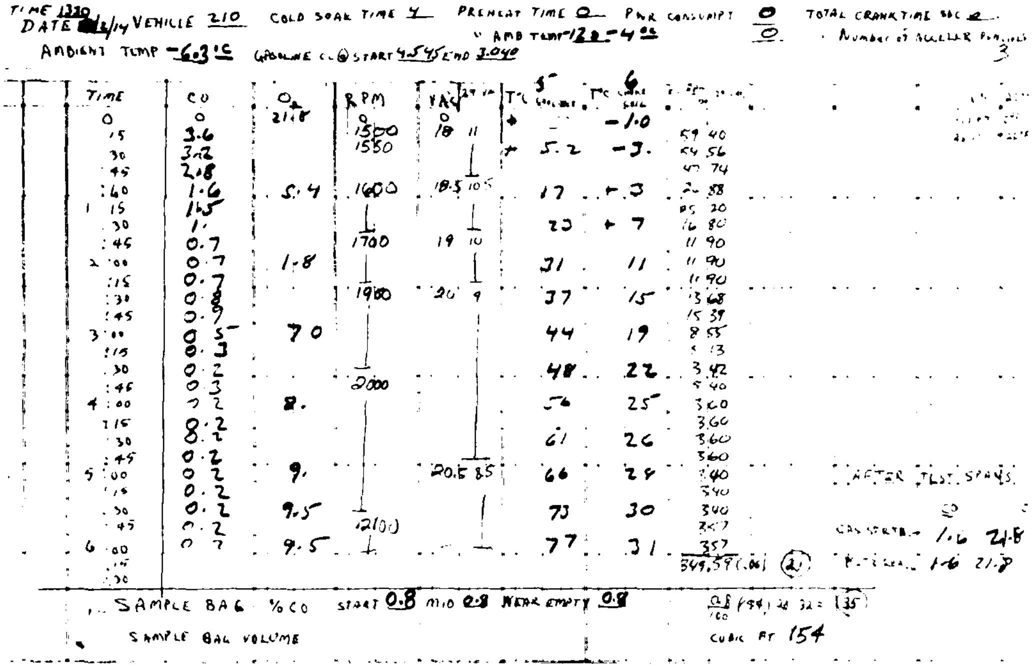


Figure 2. Typical data sheet.

stabilized by remaining constant for 1 min, the cold start was considered completed. A typical data sheet is shown in Figure 2.

Bag method

The simplest and most accurate method to measure exhaust gas volume is collecting the total exhaust in a very large bag. The average CO concentration is measured as the bag volume is filtered and blown through a positive displacement gas meter which is calibrated and compensated to read volume at 15°C (60°F).

An exhaust cooler (heat exchanger) was placed in the hose between the tail pipe and the bag. During a cold start, it cooled the exhaust (with alcohol/ice coolant) to prevent melting of the bag.

The filter and gas meter couldn't be connected directly behind the exhaust cooler because they would impose excessive back pressures on the engine. The setup for the collection and measuring apparatus for the bag method is shown in Figure 3.

The volume of CO within the bag was calculated as the product of bag volume and %CO/100. The bag effectively averages the variable CO concentration that it receives.

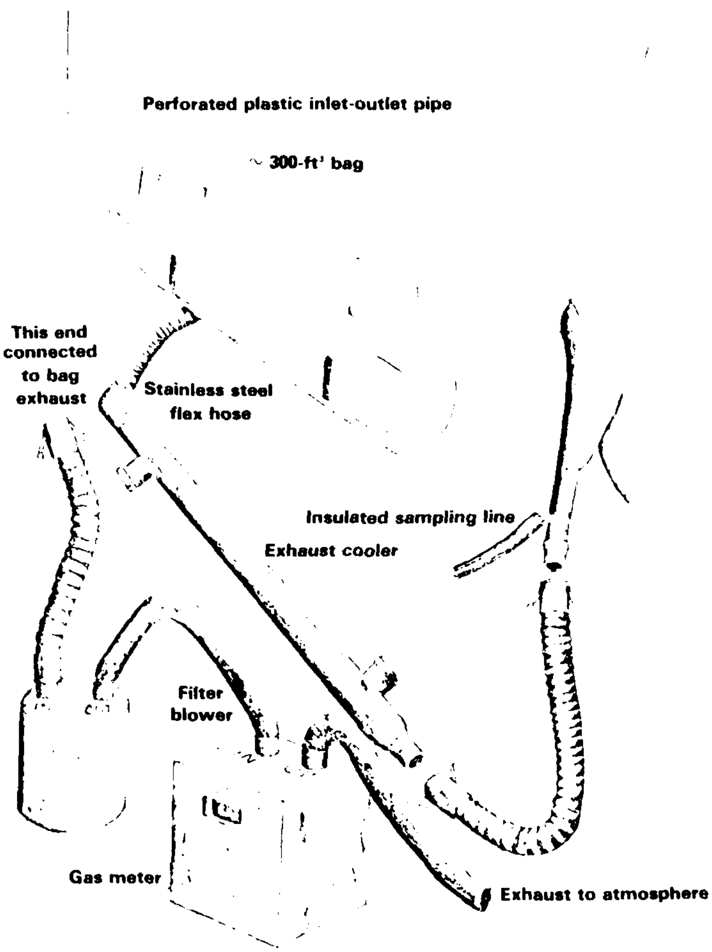


Figure 3. Collection and measurement apparatus for the bag method.

The CO measurements taken as the bag filled were used for calculations in the displacement method. The CO readings as the bag was emptied were used for calculations in the bag method.

TESTING PROBLEMS

HC measurement

As the exhaust passed through the exhaust cooler, a considerable fraction of the exhaust HCs condensed along with water vapor. This created two problems: 1) the HC/H_2O mist coated the optics of the HC sensing cell of the CO/HC analyzer thus destroying the reliability of the HC readings, and 2) the HC/H_2O mixture tended to remain in the bag, contaminating it for future runs. Since these two problems caused unreliable HC measurement,

HCs were not recorded. Holdup of CO in the bag was not a problem because it did not condense or dissolve in the condensed water.

Unstable emissions

In measuring cold-start CO emissions, one is actually observing the choking action. That action is not necessarily consistent because it depends upon mechanical linkages which may not set properly or may stick and hang up when they should be opening the choke. For example, assume that the automatic choke fails to close as the vehicle is started. The engine might not quit because the high speed idle linkage can keep it from stalling as long as it is not loaded; however, a choke that is stuck open will cause the engine to emit very little CO during a cold start. On the other hand, if the choke sticks shut the high cold-start CO emission levels may continue even after the engine warms up.

The truck had an unstable idle mixture circuit. At the beginning of the tests, its warm idle was ~1% CO, but it increased to 10% CO after one month. The mixture screw limiter cap was then removed and the mixture adjusted to ~1% CO. After two weeks the mixture dropped to less than 0.1% CO and the engine wouldn't idle. The mixture was then readjusted.

These inconsistent choking actions kept the cold-start tests from being very precise. There was considerable scatter in the test data, particularly for the truck (larger engine). The extent of the emissions data scatter is indicated by the fact that for many of the multiple near-duplicate tests, the standard deviations varied from 50 to 100% of the mean.

Defective preheater

The preheater thermostat on the Datsun 310 intermittently stopped the preheater. The preheater was replaced, but the problem continued. The cause was not isolated, but it was thought that the thermocouple wires in the heater hose may have caused an airlock which restricted circulation from the preheater. Questionable with-preheat data from the Datsun 310 were not used. The coolant temperature readings were used to verify preheater operat: ; however, no coolant temperatures will be discussed in this report.

Furnace

The garage was the cold test chamber. A low temperature thermostat was attached to its furnace to allow control of temperatures down to -30°C (-22°F). At temperatures of -18°C (0°F) or less, furnace malfunction was

prevalent, necessitating that the emissions data be grouped in temperature ranges rather than listed at specific temperatures.

Weather

The tests were planned during December, January and February so that low ambient temperatures would be available. But the weather was either very cold, below -29°C (-30°F), or very warm, -12°C (+10°F) or more. The furnace didn't work during the very cold weather. In addition, a week of above 0°C (+32°F) temperatures in January and two weeks of above -7°C (+20°F) temperatures in February limited the amount of testing. February 1980 was the warmest Fairbanks February on National Weather Service records.

Back pressure

It was realized that attaching an exhaust cooler and bag to the tail pipe of the vehicles would increase the exhaust system back pressure to the extent that it might restrict flow. To partly compensate for this effect, the muffler was removed from the pickup truck engine. Back pressure readings were taken on the exhaust pipe just upstream of the catalytic converter. At 1500 rpm, with the original exhaust system and muffler, the reading was 8 cm (3 in.) of water. Without the muffler, but with the bag and exhaust cooler, the back pressure was 23 cm (9 in.) of water. The 15-cm (6-in.) pressure increase was not considered significant since engine operation at no-load conditions did not appear to be affected.

Because of the much smaller engines in the Datsuns, their increase in back pressure was expected to be less than 5 cm (2 in.) of water. For comparison, normal road-load back pressure at 50 mph is usually from 25 to 75 cm (10 to 30 in.) of water.

During a few of the lower temperature tests, exhaust condensate plugged the 5-cm (2-in.) hose between the cooler and bag. When this happened the hose jumped about the floor because of pressure pulsations from the engine (exhaust valve opening and closing). The resulting increase in back pressure (perhaps 30 cm [12 in.] of water) didn't affect the engine's operation and the problem was alleviated by shaking the hose to break the plug.

RESULTS AND DISCUSSION

The three vehicles used in the cold-start tests were a Dodge light-duty truck with a 3.7-L (225-in.^{3}) engine, a 1976 Datsun 210 and a 1979 Datsun 310. The Datsuns had the same 1.4-L engine and emission controls so it was decided to see if there was any difference in their emissions. Student's t-test was used to compare emissions at all cold-soak conditions without preheat. There were no significant differences between the 210 and 310 emissions at the 10% level of significance.

Fuel consumption for the 1.4-L engines appeared to be greater than that for the large engine. It was suspected that the carbon canisters (for evaporation control) were affecting the inventory in the weigh tanks. Since the figures do not make sense they will not be presented in this report.

COMPARISON OF ENGINE DISPLACEMENT AND BAG METHODS

In this study 112 cold-start tests were performed. Instrument or other failures reduced by six the number of tests that provided enough information for calculating CO emission from both the engine displacement and the bag sampling method. Since it captures all the exhaust, the bag method is the more accurate. A linear regression was used to determine the correlation between the two methods. In the regression equation, let y be the CO in liters from the engine displacement method and let x be the CO in liters from the bag method.

For the 1.4-L engine with an air pump the equation is

$$x = 1.45\ y - 16.$$

The correlation coefficient is 0.81. For the 3.7-L engine with an air pump the equation is

$$x = 1.52\ y - 177.$$

The correlation coefficient is 0.79. The air pump displacement was not added to the engine displacement because it wasn't done in earlier research and because the air pump output is not directly proportional to engine rpm. The constants in the equations represent (to some extent) the air pump displacement and the fact that when CO is formed there are fewer moles of reactants than the moles of combustion products. For the balanced

combustion equations see Appendix B. Also, a method of compensating for exhaust dilution due to air pumps in the engine displacement method is developed in Appendix C.

The data scatter between tests due to inconsistent choke action does not show up in the regression equations because the same exhaust sample from each cold start was used for each measuring method (displacement and bag). The correlation coefficients of 0.81 and 0.79 indicate that results from both methods have a high probability of being related to each other.

Prior to this report, cold-start test results in Alaska were calculated using the engine displacement method. By use of the two regression equations, it is possible to more accurately estimate the CO emission from 4- and 6-cylinder engines that are equipped with air pumps.

In all prior work, the mass emissions were calculated assuming the CO volume was at 0°C and 760 mm Hg. At those conditions the CO density is 1.25 g/L. In this study the gas meter was calibrated and compensated to read at 15°C (60°F) and used at 737 mm Hg (29 in. Hg); therefore, the CO volume was calculated at those conditions. The CO density at 15°C and 737 mm Hg is 1.148 g/L.

Since the correlation coefficients were high, conclusions from prior research using the engine displacement method are generally valid; the vehicle operating mode that creates most of the CO in the Fairbanks central business district is cold start (Fairbanks North Star Borough 1977) and engine preheaters can reduce cold-start CO emissions (Leonard 1978).

COLD-START CO WITHOUT PREHEAT

Prior studies, using only overnight cold-soak periods and loaded engine tests, found that temperature had a significant effect on emissions. As the soak and test temperature were lowered the CO emissions increased substantially, by a factor of two or more for carbureted engines (Ostrouchov 1978).

Local Alaskan investigators also examined the effect of temperature and length of cold-soak periods (Leonard 1978). Leonard concluded that the length of the cold-soak period had more effect on cold start (unloaded engine) emissions than did cold-soak temperature.

Data scatter

There was considerable data scatter in the cold-start results. Inexperience with the new test procedure may have contributed to this. The exact cause is not known, but the following two items may account for some of the scatter: lack of a constant soak temperature and lack of precision in typical automatic choke action. Because of considerable choking action, carburetors and induction systems undergo their widest swings in air-to-fuel ratios during cold start. For example, see the discussion in the Unstable emissions section. The relationship between air-to-fuel ratios and CO emission is discussed in Appendix A.

One set of the near duplicate tests yielded CO emissions that differed by a factor of 80 to 1. However, results from most duplicate tests were within 100% (a factor of 2 to 1) of each other. All the cold-soak bag results are tabulated in Appendix D. None of the tests were at a constant temperature; therefore, the mean or the range was tabulated. In the only other similar cold-start study (Leonard 1978) results from one near-duplicate set differed by a factor of 70 to 1. Leonard also reported that he found data scatter in the FTP-CVS tests of other investigators of low temperature automobile emissions.

Only the results from the bag method will be discussed from here on. The data scatter was probably caused by inconsistent engine cold-start emissions. These inconsistent emissions would not affect the displacement-bag correlation because in all cases the same emission sample was used for each test. However, inconsistent engine warmup emissions would cause uncertainty in the temperature effect and preheat effect studies.

CO vs temperature

For all overnight cold soaks, the CO emitted versus soak and test temperature is plotted in Figure 4. The line is the linear regression line for the data from the 1.4-L engines from -5° to -20°C. The equation for that line is CO = 85 - 1.4 (°C). The correlation coefficient is 0.14, a very poor correlation. The negative slope of 1.4 g CO/°C shows that the CO emission may increase with decreasing temperature. The CO values at 20°C are for 6 hr of cold soak. They fall below an extension of the regression line which indicates that for a wider temperature range the temperature effect may be even greater, i.e. slope greater than -1.4.

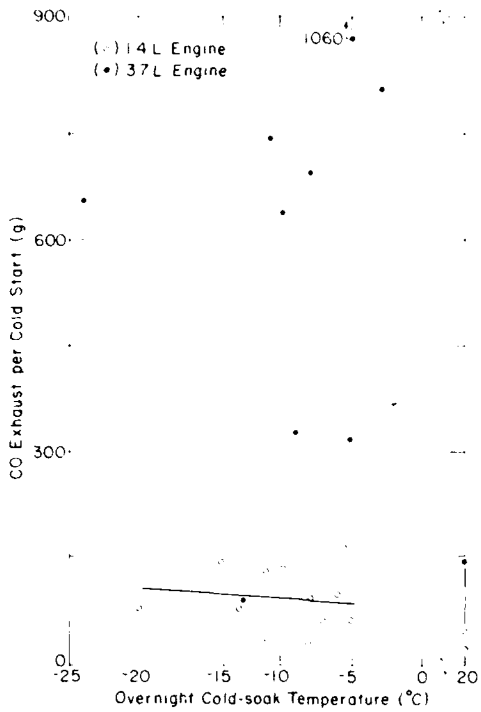


Figure 4. The effect of temperature on cold-start CO production (no preheater use).

The data for the 3.7-L engine are too widely scattered to attempt any analysis. All that can be said is that at the 20°C test the CO emission is lower than 8 of the 9 colder tests.

CO vs cold-soak time

At temperatures of 0° to -30°C, a decrease in temperature does not appear to cause a large increase in cold-start CO emissions. Therefore, for further analysis, temperatures will not be considered as the important variable. Now an examination of the effect of cold-soak time is in order. Because the larger engine's emissions were much greater than the smaller engine's, they will be analyzed separately.

Figure 5 shows the effect of cold-soak time upon CO emissions for the various temperature ranges for the 3.7-L engine. The line is drawn through the mean of the data for all temperatures. From this chart it appears that the CO emissions increase with soak time until about 9 hr. There is not enough data for the 9-hr and longer soak times to make any quantitative statement, but it appears that the CO emissions may not increase much after

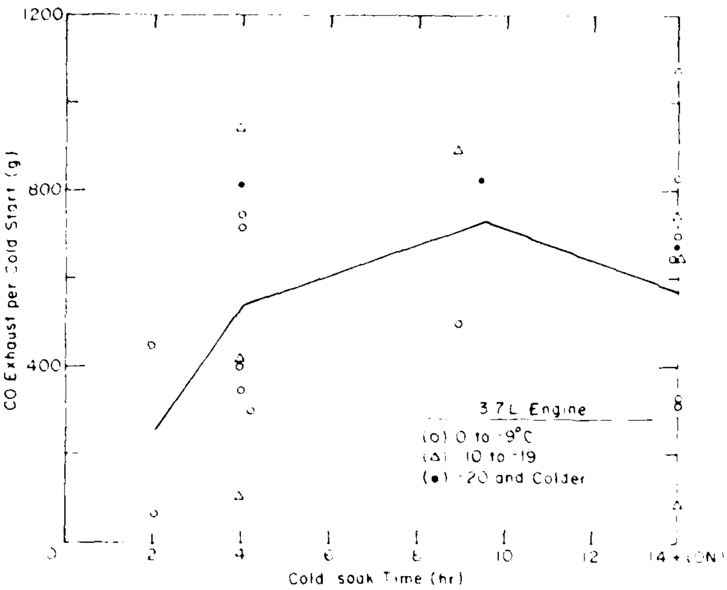


Figure 5. The effect of the length of cold-soak time on cold-start CO production by the 3.7-L engine (no preheater use).

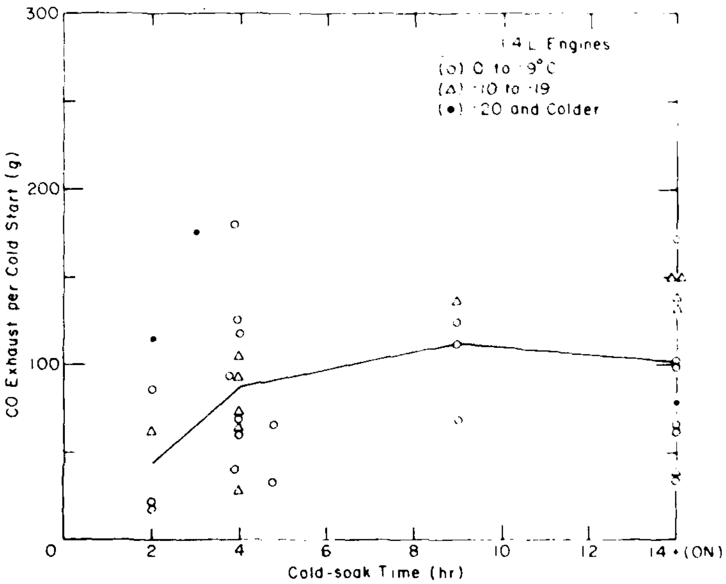


Figure 6. The effect of the length of cold-soak time on cold-start CO production by the 1.4-L engines (no preheater use).

~ 9 hr of cold soak. Leonard's (1978) data show a similar trend for 4- and 6-cylinder (I-block) engines. However, there was no peaking at less than 12 hr of cold soak for his V8 engines.

The time effect for the 1.4-L engines is shown in Figure 6. It shows a similar trend; CO emission increased with soak time, except in this case the high point at ~ 9 hr is not as pronounced.

Because of the large amount of data scatter, the soak time effect for the I-block engines cannot be quantified other than to say that as soak time increases up to about 9 hr so does the cold-start CO emission. The slope of the line (up to 9 hr) on Figure 5 is greater than the slope on Figure 4. Therefore, it appears that the time effect is greater than the temperature effect for the limited ranges studied. However, because of large amounts of data scatter this cannot be proven.

EFFECTIVENESS OF PREHEAT

One of the major objectives of this study was to determine the effectiveness of the electric preheaters in reducing the mass of CO produced per cold start. Because of the limited number of data points and the tremendous data scatter, the results cannot be considered quantitative.

As discussed earlier, cold-soak temperatures from 0° to -30°C did not appear to have as much effect on cold-start CO emissions as did cold-soak time. Therefore, for evaluating preheater effectiveness, the data were not segregated into temperature ranges. But if the mean temperature of two separate groups differed by more than ~ 6°C, the CO data were corrected to the same temperature mean by use of the 1.4 g CO/°C factor (slope of regression line in Figure 4).

The % CO reduction due to continuous preheat for the various cold-soak times is shown in Figure 7 and was determined by dividing the CO without

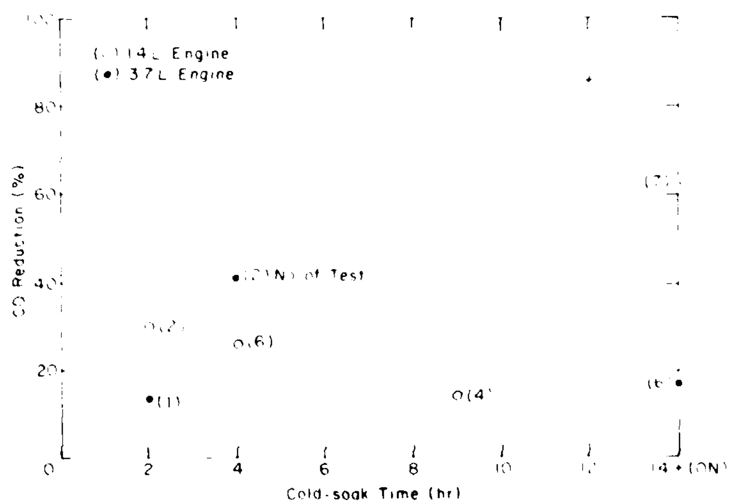


Figure 7. Percent CO reduction at various cold-soak times due to continuous preheater use (+ indicates Leonard's 1978 data).

preheat minus CO with preheat by the CO without preheat times 100. It must be recognized that the preheater-on time is included as part of the cold-soak time. The number of cold-start tests with preheat is in parenthesis beside each plotted point in Figure 7. The sole 9-hr data point for the 3.7-L engine indicated a negative reduction. The only data point of any significance was for the 1.4-L engine at the overnight (ON) soak time. For it, the t-test indicated a difference between the emissions (with and without preheat) at a 1% level of significance. For all other data points the t-test could not establish a difference between the emissions with and without preheat at the 10% level of significance. The number of tests may have been insufficient or the replicate means (g CO with and without preheat) may have been too close.

For the longer, overnight soak with continuous preheat, the 63% CO reduction for the 1.4-L engine is considerably higher than the 17% CO reduction for the 3.7-L engine. Since with this longer soak time both engines are at thermal equilibrium with the ambient, the better performance with the smaller engine may be due to a higher preheat energy level. The unit preheat watts per liter of displacement for the 3.7-L engine is 135 and 525 ± 11 for the 1.4-L engine.

In 1978 Leonard obtained an 86% composite reduction for 4-, 6-, and 8-cylinder engines at 12-hr cold soak. He probably felt that his data were too scattered for statistical tests.

The data for shorter term (partial) preheat during cold soaks were much more inconsistent than for continuous preheat. The t-test for this group did not show any difference between with and without preheat; therefore, results from analysis of the short term preheat effects will not be presented.

Because of the limited number of tests and the lack of precision, the numerical results from Leonard's study and from this study will be integrated and rounded off to one significant figure. When one considers long soak times at temperatures from 0° to -30°C a continuous preheat would be expected to reduce CO emission by 20 to 90%, depending upon the energy level of preheat.

This study has shown that preheaters are effective devices for reducing cold-start CO emissions. But, because of the large amount of data scatter, all the results cannot be proven statistically. Only the range of expected performance can be defined.

SUMMARY AND CONCLUSIONS

This study was conducted to 1) develop a quantitative method for measuring cold-start emissions and to compare it with an earlier method, 2) quantify cold-start emissions, and 3) determine the effectiveness of electric preheaters in reducing cold-start CO emissions.

The tests were limited to two different engine sizes. Inconsistent engine cold-start emissions did not affect the comparison of methods but did contribute to uncertainty in quantifying temperature and preheater effects.

A total-exhaust-capture bag method was developed and compared with the earlier engine displacement method. A linear correlation coefficient of 0.8 was obtained which indicates that prior conclusions drawn from research using the engine displacement method are generally valid.

The data scatter was too great to draw any firm conclusions; however, the following general statements can be made. When considering cold-start CO emission in the temperature range from 0° to -30°C, the length of cold-soak time appears to have more effect upon emissions than does soak temperature.

Electric engine preheaters effectively reduce cold-start CO emissions and if used continuously during the engine-off period they can reduce the CO emission by 20 to 90%.

LITERATURE CITED

Coutts, H.J., L.E. Leonard, and K.W. MacKenzie (1973) Cold regions automotive emissions. Fairbanks, Alaska: Geophysical Institute, University of Alaska.

Environmental Protection Agency (1978) Draft advisory circular on non-FTP conditions. Ann Arbor, Michigan: EPA Office of Mobile Source Air Pollution Control.

Fairbanks North Star Borough, Department of Planning and Zoning and Department of Environmental Services (1977) Parking management study. Fairbanks, Alaska.

Holty, J.G. (1973) Air quality in a subarctic community, Fairbanks, Alaska. Arctic, vol. 25, no. 4, p. 292-302.

Leonard, L.E. (1975) Cold start automotive emissions in Fairbanks, Alaska. University of Alaska Pub. UAG R-239, Fairbanks, Alaska.

Leonard, L.E., T. Scarborough and H. Black (1978) Evaluation of automotive engine preheaters as a technique to control cold start carbon monoxide emissions. Report to Fairbanks North Star Borough, Fairbanks, Alaska.

Ostrouchov, N. (1978) Effect of cold weather on motor vehicle emissions and fuel economy. Society of Automotive Engineers, February 27-March 3, 1978, Detroit. Paper no. 780084.

APPENDIX A: AIR TO FUEL RATIO AND CO EMISSIONS

When a cold gasoline-powered engine is started it has to be choked to get sufficient gasoline vaporization for spark ignition. A closed choke causes air-to-fuel ratios (A/F) of 12 to 1 or less. This results in an exhaust CO concentration of 5 to 12%. The relationship between A/F and exhaust CO is shown in Figure A1. That relationship is not exact because the exhaust CO is affected by many other side reactions that can occur in pulsating high temperature and pressure combustion. Also, the typical automotive engine is not one but is four, six or eight individual combustion chambers, each operating at different air-to-fuel ratios.

As the engine warms up causing the choke to open, the A/F increases following the curve in Figure A1. At warm idle the A/F ratio of newer cars is near 15:1, yielding an exhaust CO less than 1%.

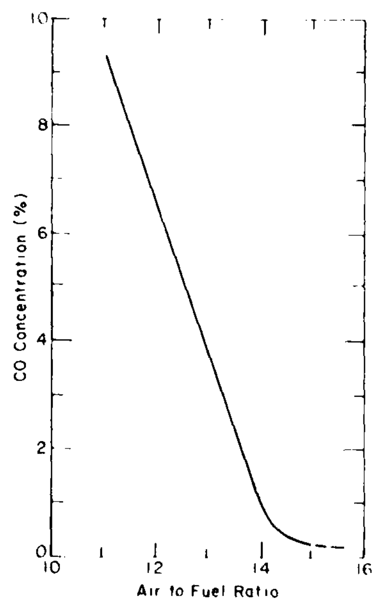


Figure A1. Exhaust gas CO emission curve.

APPENDIX B: ENGINE DISPLACEMENT METHOD FOR CALCULATION OF CO EMISSION

1. Calculation of CO emission from Dodge assuming its engine is a positive displacement compressor of 3.69 (225 in.^{3}) displacement.

$$\text{CO volume (L)} = \underbrace{\text{press. (atm)},}_{\text{PP}} \times \underbrace{\frac{\text{rev.}}{\text{min}} (1/2)}_{\text{rpm/2}} \times \underbrace{\text{displ.} \frac{(1)}{\text{rev.}}}_{\text{E.D.}} \times \text{min} \left(\frac{\%\text{CO}}{100}\right)$$

But taking data every 15 s = 0.25 min,

incremental (Δ) CO volume every 15 s is

$$\text{PP} \frac{\text{rpm}}{2} (\text{E.D.})\ 0.25 \frac{\%\text{CO}}{100}$$

where

$$\text{PP} = \left(\frac{29\text{-VAC}}{29}\right) \text{atm}$$

$$\text{Total CO vol.} = \int_{o}^{\text{end of run}} \Delta\text{CO vol.} = \sum \text{PP} \frac{\text{rpm}}{2} (\text{E.D.}) \frac{1}{400} (\%\ \text{CO})$$

$$= \sum \left(\frac{29\text{-VAC}}{29}\right) \frac{\text{rpm}}{800} (\text{E.D.})\ \%\ \text{CO}$$

$$\text{where E.D.} = \frac{225}{61.023} = 3.687\ \text{L}$$

$$\text{Total CO vol (L)} = \sum \left(\frac{29\text{-VAC}}{29}\right) \frac{\text{rpm}}{800} (3.687)\ \%\ \text{CO}$$

$$= 0.1594 \sum (29\text{-VAC}) \frac{\text{rpm}}{1000} (\%\ \text{CO})$$

2. Calculating CO Emission by Engine Displacement Method:

Datsun without correction for air pump

$$C_L = 0.0602 \left[\sum \underbrace{29\text{-VAC}}_{\text{PP}} \underbrace{\frac{(\text{rpm})}{1000}}_{\text{R}} \underbrace{(\%\ \text{CO})}_{\text{C}}\right]$$

Keystroke no.	Insert (or function)	
1	PP	
2	(x)	
3	R	
4	(X)	Redo for each 15 s interval
5	C	
6	(=)	
7	(M+)	
8	(M→X)	
9	(X)	
10	0.060	
11	= answer	

3. Gasoline combustion equation without and with CO formation:

<u>Without CO</u>

Gasoline and air → $CO_2 + H_2O + N_2$

$C_7H_{13} + 10.25\ O_2 + 38.55\ N_2 \rightarrow 7.0\ CO_2 + 6.5\ H_2O + 38.55\ N_2$

moles: $1.0 + 48.80 = 49.80 \rightarrow 7.0 + 6.5 + 38.55 = 52.05$

$$\text{increase in moles} = \frac{52.05-49.80}{49.80} = 0.045 \text{ or } 4.5\%.$$

<u>With ~10% CO dry basis</u>

Neglecting CO_2:

$$0.1 = \frac{CO}{CO+38.55},\ 3.855 = 0.9(CO),\ CO = 4.28 \text{ moles}$$

$$C_7\ H_{13} + \text{Air} \longrightarrow CO + CO_2 + H_2O + N_2$$

moles: $1.0 + 38.77 = 39.77 \quad 4.28 + 2.72 + 6.5 + 30.51 = 44.01$

$$\text{increase in moles} = \frac{44.01-39.62}{39.62} = 0.107 \text{ or } \underline{11\% \text{ more moles}}.$$

Actual % CO = 13 (dry basis). Conclusion: For more incomplete combustion, i.e. more CO formed, the moles of products per mole of reactants becomes greater.

APPENDIX C: FORMULAS TO ACCOUNT FOR EXHAUST DILUTION WITH AND WITHOUT CO OXIDATION IN THE EXHAUST SYSTEM

1. Formula of correction factors for CO concentration (on a 0% dilution air basis) in exhaust gas that has been diluted with air.

Material Balance

$$\begin{array}{lcl}
a\ CO & & a\ CO \\
b\ CO_2 & \longrightarrow \dfrac{\text{No}}{\text{RXN}} \longrightarrow & b\ CO_2 \\
c\ N_2 & \uparrow & d\ O_2 \\
 & & (c+3.76d)\ N_2 \\
 & \text{air} = dO_2 + 3.76d\ N_2 &
\end{array}$$

where a, b, c, d, ect. = moles of respective gases

let: $(a + b + c) = K$, $a + b + c + 4.76d = K + 4.76d$

eqs

(1) measured quantities: (1) $\%\ CO_{\substack{\text{actual}\\\text{reading}}} = \dfrac{a(100)}{K+4.76d}$ w/dilution air

(2) (2) $\%\ O_2 = \dfrac{d(100)}{K+4.76d}$

(3) Find: $\%CO_{ND} = \dfrac{a(100)}{K}$ = with no dilution air (ND)

(4) from (2) $d = \dfrac{\%\ O_2 K}{100-4.76(\%\ O_2)}$; $\dfrac{4.76d}{K} = \dfrac{4.76(\%\ O_2)}{100-4.76(\%\ O_2)}$

(3)/(1) = (5) $\dfrac{\%\ CO_{ND}}{\%\ CO_{\substack{\text{actual}\\\text{reading}}}} = \dfrac{a(100)}{K} \times \left(\dfrac{K+4.76d}{a(100)}\right) = 1 + \dfrac{4.76d}{K}$

(4) into (5) $\%\ CO_{ND} = \%\ CO_{\left(\substack{\text{actual}\\\text{reading}}\right)} \left[1 + \dfrac{4.76\ (\%\ O_2)}{100 - 4.76\ (\%\ O_2)}\right]$

(6) $\%\ CO_{ND} = \%\ CO_{\left(\substack{\text{actual}\\\text{reading}}\right)} \left[\dfrac{100}{100-4.76\ (\%\ O_2)}\right]$

2. Exhaust gas concentrations - conversion to a common basis.

What follows is the development of concentration correction formulas for exhaust CO, involving oxidation and dilution downstream of the engine. At a 5°C (40°F) dew point, % H_2O vapor < 0.5; therefore, all calculations are on a dry gas basis. Neglect CO_x formation from oxidation of HC in exhaust since HC is in ppm, i.e. less than 0.1%, usually.

Consider air injection in two stages: the first stage causes oxidation; the second dilution. Lower case letters represent number of moles. RXN is reaction.

Condition:	(1)	1st stage oxidation	(2)	2nd stage dilution	(3)
	a CO b CO_2 c N_2	$\longrightarrow$ RXN $\uparrow$ $\underbrace{}$ $dO_2+3.76dN_2$	$(a-2d)CO$ $(b+2d)CO_2$ $(c+3.76d)N_2$	$\longrightarrow$ $\uparrow$ (NO RXN) $eO_2+3.76eN_2$	$(a-2d)CO$ $(b+2d)CO_2$ $[c+3.76(d+e)]N_2$ eO_2
Total moles	$(a+b+c)=k$	$(a+b+c+3.76d) = k+3.76d$		$(a+b+c+3.76d+4.76e)=3.76d+4.76e+k$	

<u>Eq no.</u> and operation

% CO/100, before RXN condition (1) can be measured or calculated, is defined as C_B

(1) Definition: $C_B = \frac{a}{(a+b+c)}$

at 0% dilution air

$a = C_B k.$

% CO/100, after RXN (before dilution) condition (2) can be calculated from % CO/100 condition (3) and % O_2, see previous page.

i.e. $\%\ CO_{cond(2)} = \%\ CO_{cond(3)} \left[\frac{100}{100-4.76(\%O_2)}\right]$

label $\frac{\%\ CO}{100}$ cond(2) $= C_A$.

(2) Definition: $C_A = \frac{(a-2d)}{k+3.76d}.$

Find final % CO/100 condition (3) on the basis of total moles dilution air free and after oxidation, but at condition (1); label it CRD. Note: condition (2) has N_2 dilution.

(3) Definition: $C_{RD} = \frac{(a-2d)}{(a+b+c)} = \frac{(a-2d)}{k}$

$$= \frac{a}{k} - \frac{2d}{k}$$

(1) into (3) = (4) $\quad C_{RD} = C_B - \frac{2d}{k}$

(1) - (2) $\quad C_B - C_A = \frac{a}{k} - \frac{(a-2d)}{k+3.76d} = \frac{3.76ad + 2\ dk}{k(k+3.76d)}$

= (5) $\quad (C_B - C_A)\ k\ (k+3.76d) = 3.76ad + 2dk$

(1) into (5) $\quad k(C_B - C_A) = d(3.76C_A + 2)$

= (6) $\quad \frac{2d}{k} = \frac{2(C_B - C_A)}{(3.76\ C_A + 2)}$

(6) into (4) $\quad C_{RD} = C_B - \frac{(C_B - C_A)2}{(3.76C_A + 2)}$

= (7) $\quad C_{RD} = \frac{C_A\ (3.76\ C_B + 2)}{(3.76\ C_A + 2)}$

Therefore, exhaust oxidation devices can be evaluated and compared at steady state by measuring only % CO and % O_2 at conditions (1) and (3) and using formula (7).

APPENDIX D. COLD-START DATA.

Table D1. Bag method results.

DATSUNS 1.4-L engine

Without preheat

Temp (°C)	Soak Time (hr)	CO (g)
- 5.3	ON	170
-11	ON	38
-17 to -12	ON	79
-13.3	ON	78
- 6	ON	101
- 8	ON	34
- 4.5	ON	65
-14.3	ON	149
-7.2 to -8.5	ON	98
- 6 to -8	ON	64
-11	ON	133
-17	ON	149
- 9.8	ON	137
-3.5	9	124
-9.8 to 10.7	9	137
-7.5	9	113
-5 to -3.8	9	69
-10.8	4	29
- 6	4	180
-4 to -12	4	40
- 9	4	94
-4 to -8	4	66
- 9.6	4	66
- 9	4	118
-5 to -7	4	67
-18	4	95
- 2	2	22
- 2	2	18
-21	2	114
-19.3	2	63
-12.8	2	106
-10.5	2	72
-17.3	2	87
- 7	4 2/3	34
- 9	4	125
-20	3	176
-5 to -8	4.4	63

With continuous preheat

Temp (°C)	Soak Time (hr)	CO (g)
-9 to -12	ON	24
-8 to -15	ON	55
-3.8	ON	35
-7.7	ON	32
-8 to -9	ON	93
-5.4	ON	9.9
-25 and less	ON	9.3
-26	9	97
-6 to -11	9	115
-27	9	172
-9	9.3	105
-7	4.7	44
-6 to -9	4	64
-24	4 1/3	103
-23.5	4	29
-4 to -8	4	48
-9	4	98
-9.6 to -10.7	2	37
-20	2	48

With short preheat time

Temp (°C)	Soak time (hrs)	Preheat time (hrs)	CO
-16	ON	4	38
-16 to -17.7	ON	2	128
- 9 to -11	ON	2	137
-11.6	ON	2	84
-7.4	ON	2	53
-35	ON	4	161
-21	ON	4	31
-19	ON	2	202
-21.8	ON	4	111
-18	ON	4	195
-11	ON	0	133
- 4 to -10	ON	2	80
-12.9	ON	2	52
-9.8	ON	2	2
-18.6	11	2	156
-11	9	2	54

Table D1. (Cont'd).

Truck 3.7-L Engine

Without preheat			With continuous preheat		
Temp (°C)	Soak Time (hr)	CO (g)	Temp (°C)	Soak Time (hr)	CO (g)
- 5.2	ON	326	-17 to -16	ON	1480
-10	ON	641	-18.7	ON	44
-11	ON	749	-22.8	ON	19
-12.7	ON	93	- 9.8	ON	830
-24	ON	657	- 8	ON	457
- 8	ON	700	- 2	ON	145
- 5	ON	1060	-12	10-1/4	957
- 3	ON	819	- 7 to -27	9	883
- 9	ON	33	- 3	4	270
-22.5	9.5	817	- 7	4	357
- 3	9	499	- 3	4.1	326
-13 to 8.6	9	889			
-10.6	4	413			
-13.7	4	107			
-13.3 to -18	4	956			
-20	4	814			
- 8	4	751			
- 9	4	724			
- 5	4	353			
- 3	4	400			
- 7	4.2	307			
- 7 to -10	2	72			
-1.8	2	442			

With short preheat time

Temp (°C)	Soak time (hrs)	Preheat time (hrs)	CO
-21	ON	4	375
- 9	ON	2	626
- 8	ON	2	779
-16	ON	2	600
-10	9	2	695
- 9.3	2.2	2.2	224

ON is overnight (longer than 12 hr).

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